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Aggregating Available Soil Water Holding Capacity Data for Crop Yield Models

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16. Abstract <p>The total amount of water available to plants that is held against gravity in a soil is usually estimated as the amount present at -0.03 MPa average water potential minus the amount present at -1.5 MPa water potential. This value, designated available water-holding capacity (AWHC), in this study is a very important soil characteristic that is strongly and positively correlated to the inherent productivity of soils. In various applications, including assessing soil moisture status over large areas, it is necessary to group soil types or series as to their productivity. Current methods to classify AWHC of soils consider only total capacity of soil profiles and thus may group together soils which differ greatly in AWHC as a function of depth in the profile. This paper describes a general approach for evaluating quantitatively the multidimensional nature of AWHC in soils.</p> <p>Data for 902 soil profiles, representing 184 soil series, in Indiana were obtained from the Soil Characterization Laboratory at Purdue University. AWHC for each of ten 150-mm layers in each soil was estimated, based on soil texture and parent material. A multivariate clustering procedure was used to classify each soil profile into one of 4, 8, or 12 classes based upon ten-dimensional AWHC values. The optimum number of classes depends on the range of AWHC in the population of soil profiles analyzed and on the sensitivity of a crop to differences in distribution of water within the soil profile. This multivariate clustering approach better describes the moisture supplying capacity of soils than the simple univariate approach which uses only total AWHC of the soil profile. We conclude that this multivariate approach is a significant advancement in depicting the dynamic nature of soil moisture and represents a general quantitative approach for classifying soils for crop yield models.</p>			
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AGGREGATING AVAILABLE SOIL WATER-HOLDING CAPACITY DATA
FOR CROP YIELD MODELS

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ABSTRACT

The total amount of water available to plants that is held against gravity in a soil is usually estimated as the amount present at -0.03 MPa average water potential minus the amount present at -1.5 MPa water potential. This value, designated available water-holding capacity (AWHC), in this study is a very important soil characteristic that is strongly and positively correlated to the inherent productivity of soils. In various applications, including assessing soil moisture status over large areas, it is necessary to group soil types or series as to their productivity. Current methods to classify AWHC of soils consider only total capacity of soil profiles and thus may group together soils which differ greatly in AWHC as a function of depth in the profile. This paper describes a general approach for evaluating quantitatively the multidimensional nature of AWHC in soils.

Data for 902 soil profiles, representing 184 soil series, in Indiana were obtained from the Soil Characterization Laboratory at Purdue University. AWHC for each of ten 150-mm layers in each soil was estimated, based on soil texture and parent material. A multivariate clustering procedure was used to classify each soil profile into one of 4, 8, or 12 classes based upon ten-dimensional AWHC values. The optimum number of classes depends on the range of AWHC in the population of soil profiles analyzed and on the sensitivity of a crop to differences in distribution of water within the soil profile. This multivariate clustering approach better describes the moisture supplying capacity of soils than the simple univariate approach which uses only total AWHC of the soil profile. We conclude that this multivariate approach is a significant advancement in depicting the dynamic nature of soil moisture and represents a general quantitative approach for classifying soils for crop yield models.

INTRODUCTION

Models for large area yield predictions frequently require a soil water balance submodel to estimate the available soil moisture throughout the growing season.* However, most soil water models are running budgets that depict input, output, and balance. They require information about the plant-available water-holding capacity of each soil in order to estimate soil moisture accurately. Available water-holding capacity (AWHC) represents the maximum amount of water held in the soil between 0.03 and 1.5 MPa (0.3 and 15 bars) tension (2,16). Grouping

* Holt, D.A., C.S.T. Daughtry, H.F. Reetz, and S.E. Hollinger. 1979. Separating soil and water effects in a large area yield prediction. Agron. Abstr. 71:12.

soils by AWHC produces classes that can be used in the soil water balance models to improve the accuracy of crop yield models predictions. Additionally, by combining many different soil profiles with similar AWHC into a few classes, the time required to compute the soil water balance is greatly reduced. Several of the current methods of classifying AWHC of soils consider only the total capacity of soil profiles and as a result may group together soils which differ greatly in AWHC as a function of depth in the profile and which differ substantially in their productivity potential.

One of the chief difficulties in classifying or using information about soils is that soils do not fall into discrete units but exist in a continuum which is only artificially divided. In dealing with soils information on a large area basis and in trying to relate the use of soils to their environment, one must recognize that the discontinuities in the classification schemes also impose some problems. In a natural classification system, classes are more easily remembered and comparisons between classes are often easier than in quantitative classification systems (6). Natural classification systems frequently rely on soil genetic theory to assign a soil to a particular class. Two disadvantages of this system are that the soil genetic theory may change and the assignment of a soil to a class may be very subjective.

The numerical taxonomy is a natural system of classification in some respects. In the numerical ordination systems, quantitative soil profile data are frequently used to calculate a multidimensional distance (1,5,9). Similar soils tend to cluster or group together in the multidimensional feature space. Thus each cluster of soils represents a soil class.

The greatest advantage of the numerical approach to classification is that the soil profile data, such as texture, cation exchange capacity, base saturation, organic matter, pH, and color are used to create the soil classes without any genetic or historic bias. At the same time this lack of genetic input is one of the main reasons that numerical classification has not been widely adopted.

There are several disadvantages to numerical soil classification. First, without a theoretical basis for determining the importance of each of the variables in the multidimensional space, a relatively minor feature, such as soil hue, may have as much importance in determining the soil class as a more important feature, such as particle size. While nonuniform weighting based upon the importance of the feature in question is possible, this process is necessarily somewhat subjective. Secondly, the soil classes that result may not be related to any readily rememberable criteria or features and thus one of the purposes of classifying soil (6) is not fulfilled.

In a recent series of publications, several scientists (7,8,17,18,19), have emphasized a statistical and quantitative approach to identify the soil properties which relate to upland soil capability or productivity. The approach was quantitative, even though traditionally qualitative soil characteristics such as consistency, tilth, and structure were investigated. These soil features have numerous subcomponents which are often autocorrelated and redundant. A few independent characteristics that could be interpreted in terms of soil physical properties were chosen.

Using the principles of numerical taxonomy, Suh et al.(17,18,19) identified six fertility groups based on four statistically independent factors. Discriminant functions were developed to group any soil into one of these six classes. This series of studies, while not comprehensive enough to be applied to a wide range of soils, does provide a method to classify productivity qualitatively.

The best reason for using the quantitative approach is that it involves numerically defined limits for the classes that eliminate doubts about the classification. The quantitative approach is based on known, or at least postulated, relationships among measurable soil properties and the soils' relative productive capacity. These relative productivity indices will probably not change much as technology develops (8).

We describe and evaluate a method for grouping soils into available water-holding capacity (AWHC) classes. These classes are based upon groupings of available soil water-holding capacity profiles estimated using soil texture and parent material type. The grouping systems are compared as to their ability to distinguish potentially meaningful AWHC profile differences even when total AWHC for profiles are similar. The systems are not evaluated for their ability to group soils of similar productivity, which is the subject of another study.

APPROACH

Data on laboratory analysis and field observations for 902 soil profiles representing 184 soil series (3,11-15) were obtained from the Purdue University Soil Characterization Laboratory. These soils represented the full range of variability in water-holding capacities in Indiana soils. Additional data were obtained for selected soil series from Soil Conservation Service soil profile descriptions (Soil Conservation Service, Indianapolis, IN, unpublished data).

The available water-holding capacity (AWHC) is defined in this paper as the maximum amount of water that a soil can hold at 0.03 MPa of tension minus that at 1.5 MPa. While 0.03 MPa tension may not necessarily represent the true "upper limit" of available moisture in all soils,

Table 1. Available soil water-holding capacity based upon soil texture.

Soil Texture Classes	A Horizon	B Horizon	C Horizon
-----mm H ₂ O/mm soil -----			
Rock	0.00	0.00 [†]	0.00
Coarse sand and gravel	0.05	0.04	0.03
Gravelly loamy sand	0.07	0.06	0.06
Sands	0.08	0.07	0.06
Gravelly loams	0.10	0.09	0.09
Fine sands, loamy and loamy coarse sands, loamy fine sands and loamy sands	0.11	0.10	0.09
Sandy clays and silty clays	0.13	0.12	0.11
Coarse sandy loams and sandy loams	0.14	0.13	0.12
Fine sandy loams	0.17	0.16	0.15
Clay loams	0.18	0.16	0.15
Sandy clay loams	0.19	0.17	0.16
Very fine sandy loams, loams	0.21	0.18	0.18
Silty clay loams	0.22	0.19	0.19
Silt loams and silts	0.23	0.21	0.21
Mucks	0.30	0.30	0.30

[†] Adapted from Soil Survey Staff (13-17) and unpublished data from Soil Conservation Service, Indianapolis, IN.

it does provide a reasonable estimate for comparing various soils. AWHC was calculated for each soil horizon using the particle size distribution of the soil horizon, its position in the profile, and the factors given in Table 1. Estimated available water-holding capacity was reduced for greater bulk density in certain kinds of C horizons and fragipans that limit root penetration using factors given in Table 2.

AWHC of each 10-mm increment from the surface to a depth of 1.5 m was calculated as the product of a texture factor (Table 1) and an adjustment factor (Table 2). For example, the AWHC of a soil with a clay loam texture in the A horizon is $(0.18 \text{ mm water/mm soil}) \times (1.00) = 0.18 \text{ mm water/mm soil}$. If the same soil texture occurs below a BX fragipan, its AWHC is $(0.16 \text{ mm water/mm soil}) \times (0.67) = 0.11 \text{ mm water/mm soil}$. Each profile was represented by ten 150-mm layers, subsequently referred to as layers 1 through 10. AWHC for each of the ten 150-mm layers was calculated and expressed as mm water/150 mm of soil in that layer. The ten AWHC values for each soil profile were the ten variables used in the clustering procedures.

A multivariate cluster procedure, FASTCLUS (11), was used to aggregate the 902 soil profiles into their natural available water-holding capacity classes. Each soil profile was assigned to one of 4, 8, or 12 classes based upon the calculated ten-dimensional Euclidean distances among available water-holding capacity values.

Cumulative available water holding capacity in the top 1.5 m of each soil was also calculated. An analysis of variance with unequal cell sizes (10) and Duncan's multiple range test (10) were used to identify significant differences in cumulative AWHC among classes in the 4-, 8-, and 12-cluster analyses.

RESULTS AND DISCUSSION

Multivariate Analyses

Four Classes

Mean available water-holding capacities as a function of depth for the 4-cluster analysis are shown in Figure 1. Of the 902 soil profiles analyzed 162, 201, 305, and 234 were classified into cluster classes 1, 2, 3, and 4, respectively (Table 3). The first cluster class has the highest holding capacity in all layers and the fewest members. These soils tend to have deep profiles and consist of very high water-holding capacity textures, such as silty clay loams, silt loams, silts, or mucks.

Soils of the second cluster class have the lowest AWHC in all layers (Fig. 1). These soils have textures, such as sandy loam, sandy

Table 2. Available soil water-holding capacity adjustment factors.

Horizon Type	Adjustment Factor [†]
A Horizons	1.00
BX Fragipans	0.67
BX Fragipans	0.33
Other B Horizons	1.00
Wisconsin or Illinoian Till C Horizons	0.50
Lacustrine C Horizons	0.67
Weathered Bedrock C Horizons	0.67
Loess, Outwash, Alluvium and Other C Horizons	1.00
Bedrock, R, or RC Horizons	0.00

[†]Adapted from Soil Survey Staff (13-17) and unpublished data from Soil Conservation Service, Indianapolis, IN.

clay, and silty clays, in the upper layers of the soil profile and coarser textures, such as loamy sand and sand, in lower layers of the soil profile.

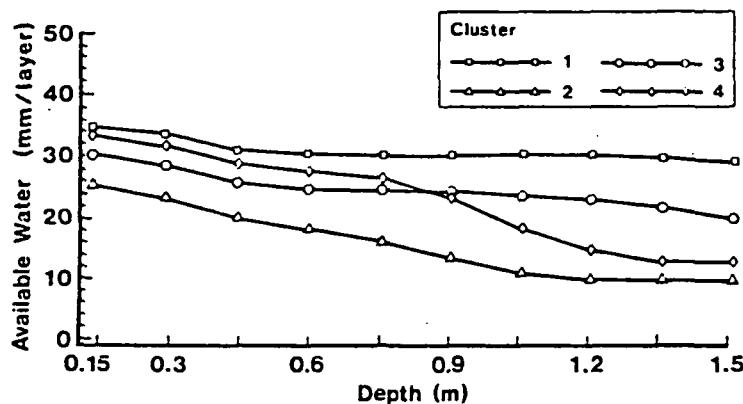
The third cluster class has an average of 29 mm AWHC in each of the first two layers, with slightly decreasing AWHC in subsequent layers. The soils of this class generally have textures with moderate to high water-holding capacity, such as clay loam and sandy clay loam, in upper horizons. and sandy loams, sandy clay, and silty clay in lower horizons.

The fourth class consists of soils with high AWHC in the top 0.6 m and rapidly decreasing AWHC in the lower portions of the profile (Fig.

1). These soils typically are very fine sandy loams, loams, or silty clay loams over compacted glacial till, rock, or residuum.

The four cluster classes are distinct in their AWHC characteristics. However, with only four classes, soils differing greatly in profile characteristics are grouped into the same class. For example, the Houghton, an organic soil, and the Ragsdale, which developed in Wisconsin Age loess, are both grouped into the first cluster class (Table 3). Similarly, the Crider, which developed in Wisconsin Age loess over limestone, and the Miami, which developed in moderately deep loess underlain by Wisconsin Age glacial till, are two very different soils included in the fourth class (Table 3). Grouping all soils into only four classes produces classes containing such widely differing soils that the usefulness of this scheme is limited.

Fig. 1. Available water-holding capacity versus depth for the 4-cluster analysis.



Eight Classes

In Figure 2 AWHC of each class of the 8-cluster analysis is plotted as a function of depth. Table 3 identifies several representative soil series in each class.

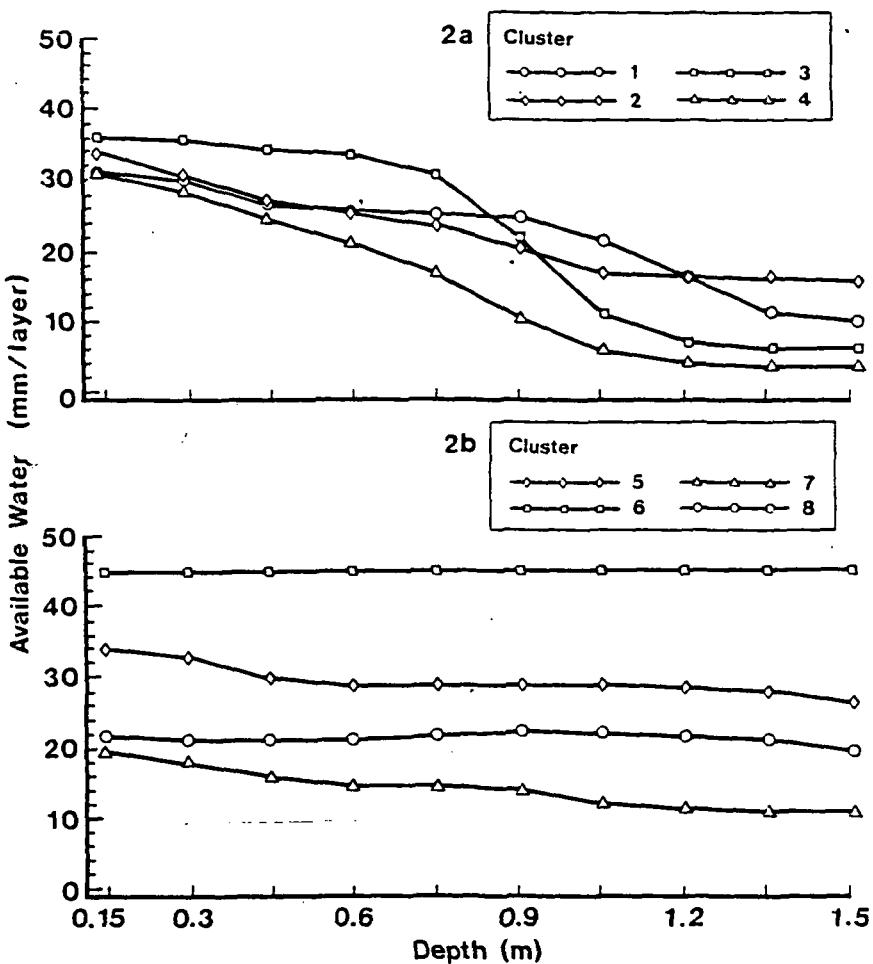
Soils of the first class are typically loams and sandy clay loams and have moderate to high AWHC in the top five layers (Fig. 2A). The lowest layers of the first class are frequently sands, loamy sands, and gravelly loams with low AWHC. The second class also has moderate to high AWHC in the first five layers. It differs from the first class in that the decrease in AWHC in the lower portion of the profile is very gradual. Soil textures of the lowest layers of the second class are sandy loams, sandy clays, and silty clays. AWHC of the third class is high for the first five layers, but then decreases very rapidly. Only the seven profiles of Muskingum, an organic soil over sand, were classified into this group. Soils of the fourth class have mean AWHC of 31 mm/layer in the top layer, AWHC decreases rapidly to less than 6 mm/layer in the lowest layers (Fig. 2A). These soils are sandy clay loams, loams, and very fine sandy loams over coarse sands and gravel.

Table 3. Representative soil series for the 4-, 8-, and 12-cluster analyses.

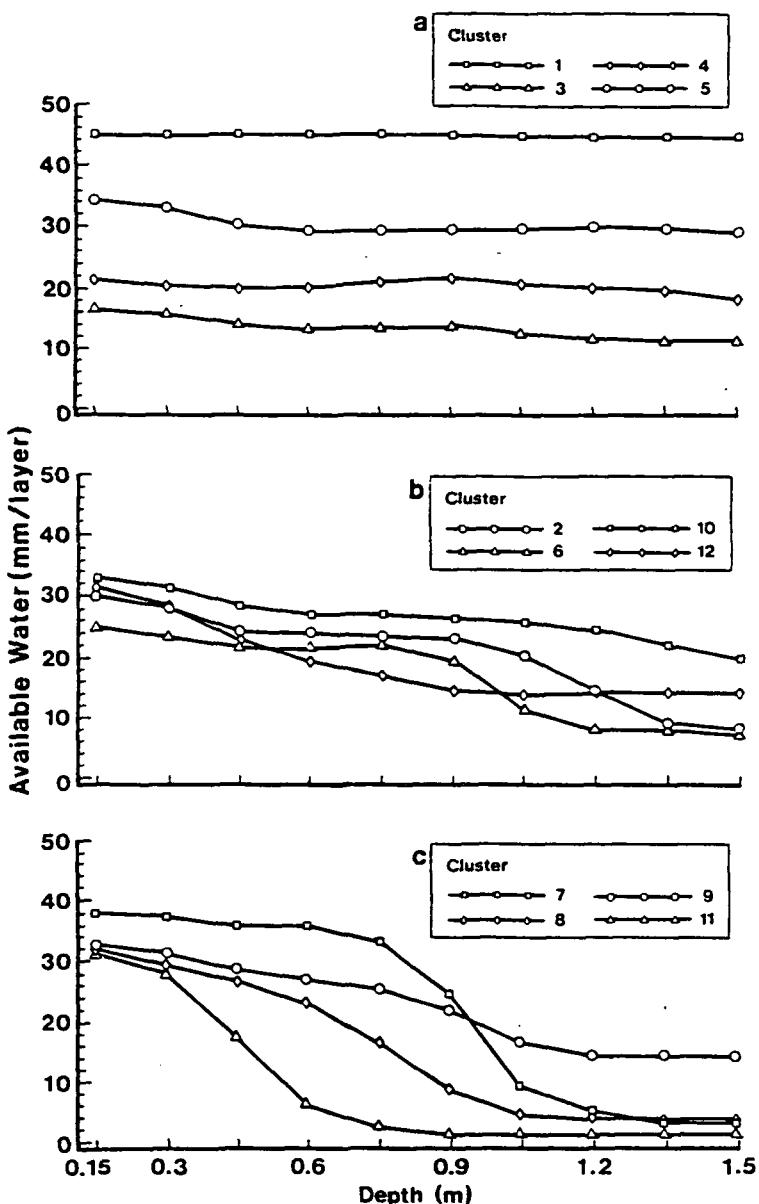
Cluster Class	n	Representative Soil Series
<u>4-cluster analysis</u>		
1	162	Flanagan, Mahalasville, Houghton, Ragsdale
2	201	Ayr, Fox, Gilford, Belmore, Maumee, Shadeland, Morley, Corydon, Adrian, Rodman
3	305	Bono, Brookston, Zipp, Vincennes, Kokomo
4	234	Alida, Muskingum, Crider, Miami, Pewamo
<u>8-cluster analysis</u>		
1	137	Alida, Pewamo, Kokomo
2	253	Fox, Crider, Miami, Brookston, Adrian, Morley, Zipp
3	7	Muskingum
4	65	Belmore, Shadeland, Rodman, Corydon
5	253	Flanagan, Mahalasville, Ragsdale
6	1	Houghton
7	107	Ayr, Maumee, Gilford
8	79	Bono, Vincennes
<u>12-cluster analysis</u>		
1	1	Houghton
2	52	Alida, Pewamo
3	65	Ayr, Maumee
4	69	Bono, Zipp, Vincennes
5	139	Flanagan, Mahalasville
6	43	Fox, Gilford
7	7	Muskingum
8	31	Belmore, Shadeland
9	176	Crider, Miami
10	228	Brookston, Ragsdale, Kokomo
11	8	Corydon, Rodman
12	83	Adrian, Morley

Figs. 2a,b. Available water-holding capacity versus depth for the 8-cluster analysis.

The fifth class (Fig. 2B) consists of deep, nearly uniform soils with high AWHC and textures, such as silty clay loams, silt loams and loams, throughout the profile. The sixth class has very high AWHC (45 mm/layer) in all ten layers. Of the 902 soil profiles, only the Houghton series, a deep organic soil, fits into this class (Table 3). The AWHC of the seventh class gradually decreases from less than 20 mm in the surface layer to less than 10 mm in the lowest layer (Fig. 2B). These soils are generally fine sandy loams overlaying sands or other coarse materials. Soils of the eighth class have low to moderate AWHC in all layers. These soils are generally coarse sandy loams, sandy clays, and silty clays.



Eight cluster classes obviously provided more types of average AWHC curves than the 4-cluster analysis. The additional classes allowed unusual or outlier soils to be represented by separate classes. For example, classes 3 and 6 contain only seven and one soil profiles, respectively; however, these soil profiles differed in AWHC from all other soil profiles used in the analyses. Classes 5, 7, and 8 of the 8-cluster analysis are similar to classes 1, 2, and 3, respectively, of the 4-cluster analysis. Classes 1 and 2 of the 8-cluster analysis are similar to class 4 of the 4-cluster analysis.



Figs. 3a,b,c. Available water-holding capacity versus depth for the 12-cluster analysis.

Twelve Classes

The 12-cluster analysis produced a wider variety of AWHC curves than the other analyses (Fig. 3). Soils represented in Figure 3A are deep, uniform soils with widely differing AWHC. The first class contains the Houghton and other deep organic soils (or mucks) with very high AWHC.

Soils of classes 3, 4, and 5 also have uniform textures throughout their profiles but have low, moderate, and high AWHC, respectively (Fig. 3A). Soils of class 3 are typically deep fine sands and loamy sands averaging 13 mm AWHC per layer. In class 4 the soils are sandy loams with 21 mm AWHC per layer. Soils in class 5 are deep silt loams and silty clay loams with 31 mm AWHC per layer. The soils of class 5 have the highest AWHC throughout the profile of the inorganic soils evaluated.

Classes 2, 6, 10 and 12 have moderate to high AWHC in the upper layers and moderate to low AWHC in the lower layers of the profile (Fig. 3B). Soils of class 10 are typically very fine sandy loams overlaying loamy sands or clay loams. The textures of surface layers of soils in classes 2 and 12 are frequently sandy clay loams or loams which contain about 25 mm AWHC per layer (Fig. 3B). The texture of soils in these classes changes gradually to fine sands and loamy sands at 1.5 m which contain an average of 12 mm of AWHC per layer. Soils in class 6 are generally fine sandy loams overlaying sands or gravelly loams.

The AWHC profiles for classes 7, 8, 9, and 11 (Fig. 3C) have high AWHC in their upper layers and low to very low AWHC in the lower layers. Class 7 contains only the Muskingum series (Table 3) which is an organic soil over sand. The textures of soils in classes 8, 9, and 11 are frequently very fine sandy loams, sandy clay loams, and silty clay loams in the surface layer. These soils typically have AWHC exceeding 30 mm per layer at the surface. However, the AWHC of these soils decreases rapidly as soil texture changes to fine sand or loamy sand for soils in class 9 and coarse sand or gravel for soils in classes 8 and 11.

In the 12-cluster analysis, several series of curves differing only in the slope of their decline in AWHC were identified (Fig. 3C). For example, classes 7, 8, and 11 all have greater than 30 mm of AWHC in the surface layer and decline to less than 5 mm/layer. The depth at which the change occurs varies among these classes. Classes 1, 3, 4, and 5 are basically parallel curves and differ nearly uniformly in their AWHC throughout the soil profile.

A quantitative evaluation of the superiority of one of these sets of cluster classes is difficult. The optimum number of classes depends on the range of data being classified. In this case, the best quantitative assessment would result in cluster classes that were similar within and differed between classes with respect to some important variable, such as productivity or soil moisture status, under a specific weather regime. This assumes that the wide variety of soil profiles in a region could be represented adequately by the AWHC cluster classes.

Univariate Analysis

The conventional way to evaluate AWHC classes of the cluster analysis is to compare average cumulative available water-holding capacities of each class. The sum of AWHC for ten layers of soil (0 to 1.5 m) represents the soil moisture that potentially would be available to a crop, such as corn or soybeans, with a fully developed root system (Table 4). While this single dimensional variable may not adequately describe the complex interactions of AWHC with growing plants as well as multi-dimensional based classes, cumulative AWHC should allow some quantitative comparisons among classes within each cluster analysis.

In the 4-cluster analysis, the cumulative water-holding capacity (0 to 1.5 m depth) of each class is significantly different (Table 4). This was expected since the curves (Fig. 1) for these four classes are simple and distinct. The multidimensional clustering of AWHC with only four classes has little advantage over the simple unidimensional classification based on cumulative AWHC.

The curves for the 8-cluster multidimensional analysis are noticeably more complex than those of the 4-cluster case. Several curves of the 8-cluster analysis (Fig. 2) appear similar to other curves in the 4-cluster analysis. The mean cumulative AWHC of classes 1, 2, and 3 of the 8-cluster analysis do not differ significantly from one another (Table 4). The soils in classes 1, 2, and 3 are very different in their AWHC profiles (Fig. 2A) and may differ in their inherent productivities. Based on cumulative AWHC, the 12-cluster analysis provided 10 statistically different classes. Those classes that were not significantly different on the basis of cumulative water-holding capacity have distinct AWHC profiles (Fig. 3B, 3C). For example, classes 7 and 9 have nearly identical cumulative AWHC at 1.5 m (Table 4). However, soils in class 7 are shallow soils underlain by coarse sand with very high AWHC only in the five upper layers and very low AWHC in the lower layers.

Table 4. Mean cumulative water-holding capacity in the top 150 cm of soil for the 4-, 8-, and 12-cluster analyses.

4-Cluster		8-Cluster		12-Cluster	
Cluster No.	Mean [†] (mm)	Cluster No.	Mean (mm)	Cluster No.	Mean (mm)
1	306 a	1	219 cd	1	450 a
2	154 d	2	229 c	2	206 e
3	243 b	3	228 c	3	133 i
4	227 c	4	156 e	4	205 e
		5	293 b	5	307 b
		6	450 a	6	168 g
		7	144 f	7	227 d
		8	214 d	8	153 h
				9	230 d
				10	268 c
				11	91 j
				12	189 f

[†]Mean values within each column followed by the same letter are not significantly different at $\alpha = 0.05$ level.

Soils in class 9 also have high AWHC in the upper five layers but have moderate AWHC in the lower layers. Similarly, classes 2 and 4 are not significantly different in cumulative AWHC at 1.5 m (Table 4) but as a function of depth AWHC of these soils changes dramatically (Figs. 3A, 3B).

For soils with relatively uniform AWHC profiles, e.g., classes 5, 6, 7, and 8 of 8-cluster analysis (Fig. 2B) and classes 1, 3, 4, and 5 of 12-cluster analysis (Fig. 3A), the cumulative AWHC should adequately represent the moisture-supplying characteristics of these soils. In cases where AWHC changes as a function of depth, the single dimensional variable, cumulative AWHC, does not adequately describe the moisture-supplying characteristics of these soils. Clearly the multidimensional approach should be superior for describing soils whose AWHC changes with depth.

SUMMARY AND CONCLUSIONS

Available water-holding capacity (AWHC) was defined as the amount of water that a soil can hold at 0.03 MPa of tension minus that held at 1.5 MPa tension. AWHC, for ten 150-mm layers in each of 902 soils, was estimated based on texture and position in the profile. A multivariate clustering algorithm was used to identify natural groupings or clusters that exist in the wide range of soil profiles from Indiana. Three cluster analyses using 4, 8, or 12 classes provided different levels of aggregating soil information. In the simplest case, using only four classes, the within-class variability was large and widely differing soils were frequently placed in the same class. In the most complex case using 12 classes, the within-class variability was reduced and subtle changes in AWHC with depth were identified. The 8-class analysis provided intermediate results.

Because AWHC as a function of depth is difficult to visualize and compute in ten-dimensional space, the total AWHC in the soil profile also was used to classify soils. While cumulative AWHC may adequately represent the total moisture-supplying capacity of relatively uniform soils, it does not account for changes in AWHC with depth. The multidimensional approach groups soil profiles with similar AWHC profiles into the same class. Thus the multidimensional approach represents the AWHC profile better than total AWHC because: (i) soils with widely divergent AWHC profiles but the same total AWHC are not placed in the same class, (ii) abrupt changes in AWHC caused by factors including glacial till, fragipans, and lithic contacts are represented, and (iii) the classes of AWHC from a multivariate analysis may provide valuable information for crop yield models with detailed soil moisture submodels. This multidimensional approach can be readily modified to include other characteristics that might affect root development and plant growth. For example, percent Al³⁺ saturation could be used to describe Al toxicity, which would restrict root development in certain horizons of some soils (4).

and thus would effectively reduce the AWHC of those soils. Finally, as new crop cultivars with tolerances to unfavorable soil conditions are developed, this multidimensional approach, coupled with accurate yield models, can evaluate the changes in AWHC and potential yields.

One might be tempted to evaluate the grouping systems on their ability to classify together soils with similar productivity indices. This would be an oversimplification of what we were trying to do. Two soils with the same average productivity might differ considerably in productivity in a specific year. The cause of this difference might be the nature of the AWHC profile rather than total AWHC of the soils. One way to test the ability of the grouping system to group soils that consistently yield at the same level is to generate the yield estimates with a simulation model operated under several carefully selected weather regimes. That is the subject of another study.

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